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## **PermaNET - Permafrost Long-term Monitoring Network. Synthesis report**

Mair, V ; Zischg, A ; Lang, K ; Tonidandel, D ; Krainer, K ; Kellerer-Pirklbauer, A ; Deline, P ;  
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Published Research Report

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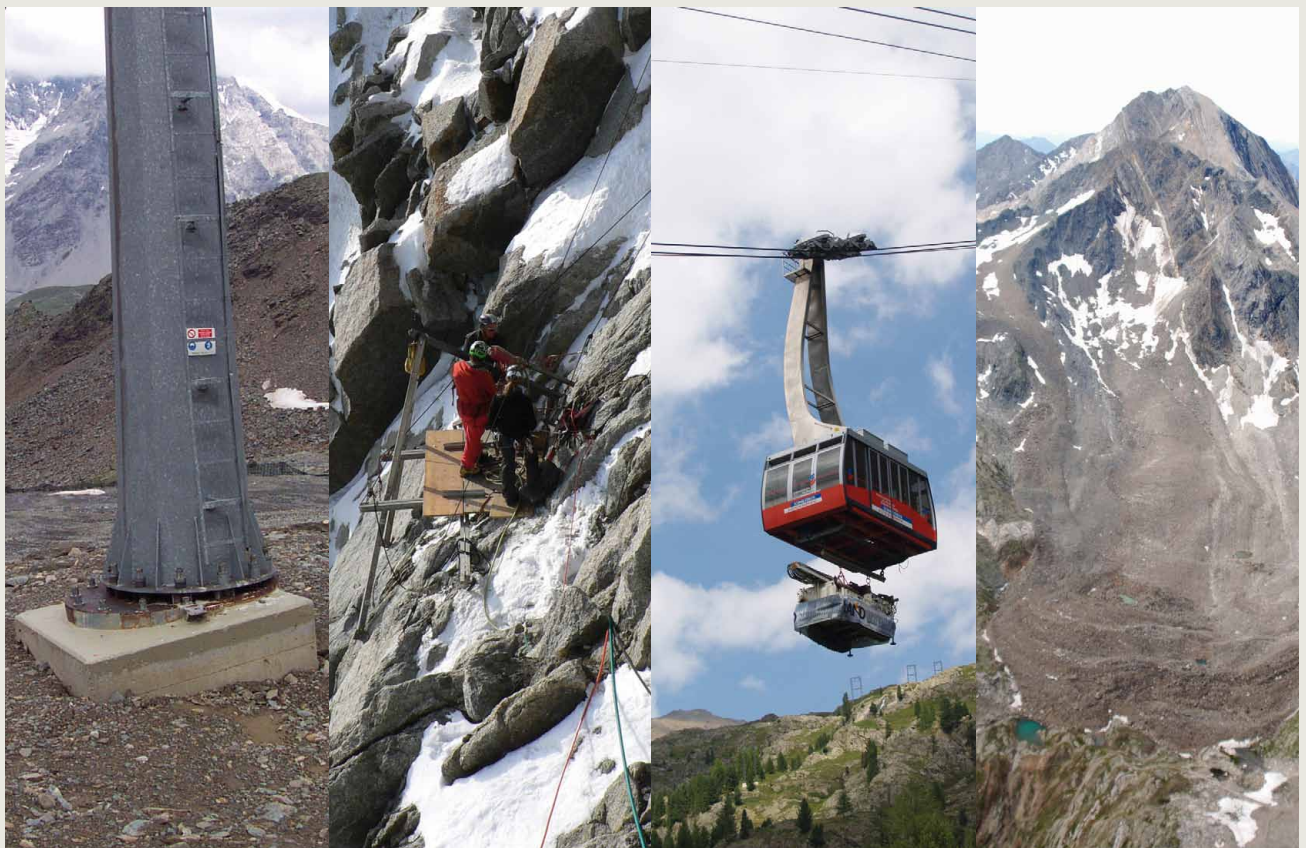
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# PermaNET

## Permafrost Long-term Monitoring Network

### SYNTHESIS REPORT



# Impressum

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# PermaNET

Permafrost Long-term Monitoring Network

## SYNTHESIS REPORT

**Cover photo**, from left to right: Soil subsidence and adjustment of foundations, photo: A. Zischg. Drillings at Aguille du Midi, photo: P. Deline. Transport of drilling equipment, photo: Geological Service Autonomous Province of Bolzano. Rock glacier near Stettiner Hütte, South Tyrol, photo: V. Mair

### Preface Lead Partner

In discussions about the possible effects of climate change in the Alps, the thawing of permafrost is often mentioned as an adverse consequence, alongside the melting of glaciers and the increase of precipitation intensity. In comparison to the melting of the glaciers, the degradation of permafrost is not directly visible in the landscape. Therefore, the analysis of permafrost distribution and the assessment of the consequences of climate change to permafrost are subject to greater uncertainties. The gaps in knowledge about this topic often lead to speculation. The media, in particular, tends to either exaggerate or neglect the consequences of permafrost degradation and related natural hazards. The main aim of the PermaNET project was to compile data and facts about permafrost distribution and the thermal evolution of permafrost in a changing climate, creating one knowledge base and objectifying discussions in this field. This required bringing scientists together with stakeholders and decision-makers in territorial planning. The Geological Service of the Autonomous Province of Bolzano, Italy initiated the PermaNET project, established the interdisciplinary partnership of 13 partners and 23 observers throughout the Alps and managed the project. The results of this intensive cooperation are now evident and outlined in this report. For the first time, a harmonized and standardized dataset of permafrost distribution in the Alps could be elaborated. The evolution of permafrost can now be monitored by an Alpine-wide monitoring network established within the PermaNET project. Bringing together all data and experiences of permafrost investigations throughout the Alps has resulted in a huge step forward in permafrost research and in natural hazard management practice. The elaborated decision basis provides valuable information for authorities and companies working in high-mountain areas. This brochure aims at summarizing the most relevant findings and to introduce the maps, databases, handbooks and guidelines elaborated by the PermaNET team.

Volkmar Mair  
Andreas Zischg

Lead Partner PermaNET

### Preface INTERPRAEVENT

Mountain permafrost is one of many aspects to be considered in natural hazards and risk management in the Alps. The assessment of natural hazards and the elaboration of hazard zone maps in permafrost affected areas is a rather complex task as the degradation of permafrost is influencing the triggering and the evolvement of natural hazards processes such as rockfalls, landslides and debris flows. This can have direct consequences for infrastructures in permafrost areas and indirect consequences for other natural hazards such as floods. As increasing air temperature has a direct impact on the thermal characteristics and the geotechnical behaviour of frozen rock and soil material climate change is another topic, which has to be taken into account.

All in all, mountain permafrost is another factor of the complex system of Alpine catchments. Hence, in high mountain areas the analysis of permafrost and related natural hazards represents one part of integrated watershed management and in some cases it plays an important role for the integrated risk management.

INTERPRAEVENT supports the exchange of knowledge and experiences between science and practitioners in the field of natural hazards and risk management. Therefore this brochure is a valuable continuation of former brochures on the documentation of mountain disasters (DOMODIS - available in English, French and German) and the brochure on drift wood (available in German only).

The PermaNET team tried to synthesize the state of the art of permafrost detection, permafrost monitoring and the consideration of permafrost in natural hazards assessment from a practitioner's point of view. Thus, this brochure contributes to the main aims of INTERPRAEVENT such as providing decision bases for stakeholders in natural hazards and risk management, presenting scientific discoveries and conclusions to practitioners and creating decision-making aids for all questions of technical, planning, administrative and economic preparedness.

Kurt Rohner, President  
Gernot Koboltschnig, Business Manager

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**Content**

Introduction	4	<hr/>
The project	5	3
The partnership	6	
Permafrost monitoring network	8	
Permafrost distribution in the Alps	10	
Permafrost and related natural hazards	16	
Permafrost and climate change	18	
Permafrost and water resources management	20	
Recommendations for decision-makers	22	



### Introduction

Permafrost is defined as lithosphere material (soil or rock) that remains at or below 0°C for more than two years. Permafrost can - but does not need to - contain water or ice. Glaciers are not permafrost. The superficial layer above permafrost is called the „active layer“ because temperatures can rise seasonally above 0°C. In the Alps, the active layer has a thickness of around 0.5 to 8 m.

In contrast to lowland permafrost, mountain permafrost is influenced highly by the mountain topography. Therefore, the distribution of mountain permafrost is spatially heterogeneous according to the strong variability of topography, geomorphology and climate conditions in the Alps.

Mountain permafrost is highly sensitive to climatic changes. During recent summers, an increased intensity and frequency of rockfalls and numerous debris flow events have been observed throughout the Alps. Examples of such events are the collapse of a moraine at Mulinet, rockfalls on the Matterhorn and Thurwieser, the debris flow event at Guttannen and numerous smaller events. Permafrost-related hazards affect traffic routes, tourism areas, infrastructures and settlements. The main challenge is how the respective authorities must consider these factors of climate change in risk prevention and regional development. In some locations, the topic has to be implemented into risk management practices. A further aspect of the importance of permafrost areas is the contribution of permafrost ice to the hydrologic regime of alpine watersheds.

With the joint development of a common strategy for dealing with permafrost and related hazards under changing climatic conditions and the creation of an Alpine-wide monitoring network, the project aims at preventing natural hazards, at contributing to sustainable territorial development and at the implementation of good governance practices.



Rock glacier. Photo: A. Zischg



Slope movement. Photo: A. Zischg



Rockfall scar. Photo: V. Mair



Erosion in fossil rock glacier deposits. Photo: A. Zischg



Soil subsidence and subsequent adjustments of foundation. Photo: A. Zischg

### The project

The overall objective of this project was to make a significant contribution towards the mitigation of natural hazards related to permafrost and manage their consequences, with specific regard to climate change impacts. To this end a common strategy for dealing with permafrost and related hazards under changing climatic conditions was developed collaboratively and an Alpine-wide monitoring network established. The PermaNET project further aimed to contribute to sustainable territorial development and the implementation of good governance practices by supporting the development of regional and local adaptation strategies by providing decision-makers and local authorities with a decision-base and strategies for dealing with these factors in their work. The spatially distributed gaps of permafrost data were to be closed and a consistent permafrost map and database for the entire Alps elaborated. Testing new and promising technologies and finding joint solutions for the adaptation of risk management practices, the project aimed to push the Alpine Space to be one of the leading model regions in the field of mountain permafrost research and permafrost monitoring.

The project activities were divided into two administrative work packages (WP), one PR work package and four scientific-technical work packages. The activities of the technical work packages were supported by WP1 „Project preparation“, WP2 „Project management“ and by WP3 „Information & publicity“. The latter also supported the distribution of the products and recommendations.

WP4 „Permafrost monitoring network“ aimed to collect metadata about existing permafrost monitoring activities in the Alps, extending the existing monitoring networks and defining guidelines for further installations. A metadata set of permafrost monitoring activities in the Alps was created. It closes information gaps and supports the establishment of a permafrost monitoring network in the Alps. In WP4 additional permafrost monitoring stations that expand ongoing monitoring activities were established and installed. The new monitoring stations provide additional data about the actual thermal state of permafrost and its temporal evolution at selected locations.

WP5 „Permafrost and climate change“ aimed to provide data about the permafrost distribution in the Alps. In WP5, an Alpine-wide inventory of permafrost evidence and an Alpine-wide map of permafrost distribution were compiled. Permafrost distribution maps provide the basis for assessing the effects of climate changes to permafrost and related processes and the basis for the elaboration of adaptation measures for different economical activities in high mountain areas. A book about the thermal and geomorphic permafrost response to present and future climate change in the European Alps was compiled to highlight recent permafrost changes and possible



Kick-off conference of PermaNET, photo: Geological Service Autonomous Province of Bolzano

future impacts of climate change to permafrost environments through case study sites in the Alpine Space. Furthermore, a handbook of methodologies and techniques for permafrost mapping and detection was elaborated to support the implementation of the techniques in practice.

WP6 „Related natural hazards“ provides the basis for the elaboration of the common strategy for dealing with permafrost and related hazards under changing climatic conditions. Recommendations for decision-makers have been developed, based on case studies of permafrost related hazards throughout the Alps.

WP7 „Water resources“ provided information about the relevance of permafrost ice for water resources management. Furthermore, they developed recommendations for regional environmental institutions of how best to analyse the quality of the spring water with particular focus on heavy metal pollution and particles.



### The partnership

Most authorities responsible for risk management activities are facing issues of permafrost and related natural hazards. However, knowledge and data regarding permafrost related problems and their consideration in natural hazards and risk management differ regionally and sectorally throughout the Alps. Permafrost is also a topical subject in research activities. Because of this, the Geological Service of the Autonomous Province of Bolzano, Italy initiated the PermaNET project and established an interdisciplinary project partnership. All partner states of the Alpine Space programme dealing with permafrost issues were involved in the project. Project partners were either national or regional authorities in the fields of natural hazards management, environmental protection agencies, forest management, hydraulic engineering, meteorology, civil protection, and water resources management. The involvement of scientific institutions supported the transfer of knowledge from researchers to decision-makers. For specific issues, observers, relevant stakeholders from NGO's, tourism industry and electric power production companies or external experts were invited to participate. National and transnational stakeholders were consulted for the elaboration of common strategies. The most relevant project observers actively followed the project activities and contributed considerably.

Since most regions of the Alps will be affected by climatic change and its consequences in permafrost areas, the co-operation between relevant decision-makers and scientists throughout the whole Alps was essential for the implementation of this project. The involvement of policy-makers, the responsible authorities for risk management and scientific institutes made it possible to find integrated solutions. Collaboration between different stakeholders and sectors coupled with close ties to other key institutions (e.g. tourism industry, drinking water supply, ski resorts, external experts) provided a wide field of experiences and allowed for an interdisciplinary and holistic approach. The transnational cooperation, through the exchange of knowledge, data and practices reduced costs in finding solutions for the adaptation of governance practices to specific effects of climate changes.



Excursion of the PermaNET team. Photo: Geological Service Autonomous Province of Bolzano

## The partnership

The project partnership was comprised of the following institutions:

### Project Partners

Autonome Provinz Bozen - Südtirol, Amt für Geologie und Baustoffprüfung / Provincia Autonoma di Bolzano, Ufficio Geologia e Prove Materiali

Bayerisches Landesamt für Umwelt, Abteilung 10: Geologischer Dienst, Wirtschaftsgeologie, Bodenschutz

ARPA Piemonte - Agenzia Regionale per la Protezione Ambientale, Dipartimento Geologia e Dissesto

Regione Autonoma Valle d'Aosta, Assessorato territorio e ambiente, Dipartimento territorio, e ambiente, Direzione ambiente

Regione del Veneto, Direzione Geologia e Attività Estrattive, Servizio Geologia

Provincia Autonoma di Trento, Dipartimento Protezione Civile e Infrastrutture, Servizio Geologico

Österreichisches Bundesministerium für Landwirtschaft, Forstwirtschaft, Umwelt und Wasserwirtschaft

Universität Innsbruck, Institut für Geographie

Universität Graz, Institut für Geographie und Regionalforschung

Zentralanstalt f. Meteorologie und Geodynamik (ZAMG), Regionalstelle für Salzburg und Oberösterreich

Université Joseph Fourier - Grenoble I, Institut de Géographie Alpine, Laboratoire PACTE-Territoires

Centre National de la Recherche Scientifique - Laboratoire EDYTEM

Grenoble INP, GIPSA-lab

Schweizerisches Bundesamt für Umwelt BAFU

### Transnational project management

Abenis Alpinexpert GmbH/srl

### Active Observers

Universität Zürich

WSL-Institut für Schnee- und Lawinenforschung SLF

### Observers

International Research Society INTERPRAEVENT

Ministero per la tutela dell'ambiente, del Territorio e del Mare, Direzione generale per la ricerca ambientale e lo sviluppo



Partner meeting. Photo: Geological Service Autonomous Province of Bolzano

Slovenian Torrent Erosion Control Service

Regione Piemonte, Direzione Ambiente, Settore Pianificazione Aree Protette

Seilbahnen Sölden

Dolomiti Superski

Skigebiet Ratschings-Jaufen

Confindustria Trento, Associazione Nazionale Esercenti Funiviari (A.N.E.F.), Sezione impianti a fune

Società degli Alpinisti Tridentini

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Direction Régionale de l'Environnement Rhône Alpes

Pôle Grenoblois Risques Naturels

Office National des Forêts - Délégation Nationale Risques Naturels - RTM, Direction Technique Restauration des Terres en Montagne

Parc National des Ecrins

Compagne des Guides de Chamonix

Amt der Tiroler Landesregierung, Abt. Geoinformation

Land Salzburg, Landesgeologischer Dienst

Land Steiermark, Landes-Umwelt-Information Steiermark (LUIS)

Land Kärnten, Hydrographischer Dienst

Land Vorarlberg, Landesvermessungsamt



### Permafrost monitoring network

Within the PermaNET project a detailed census of existing permafrost monitoring sites was conducted. The collected data was used to compile an Alpine-wide overview of the existing monitoring activities, highlight areas without monitoring activities, and formulate guidelines for the installation of further monitoring stations.

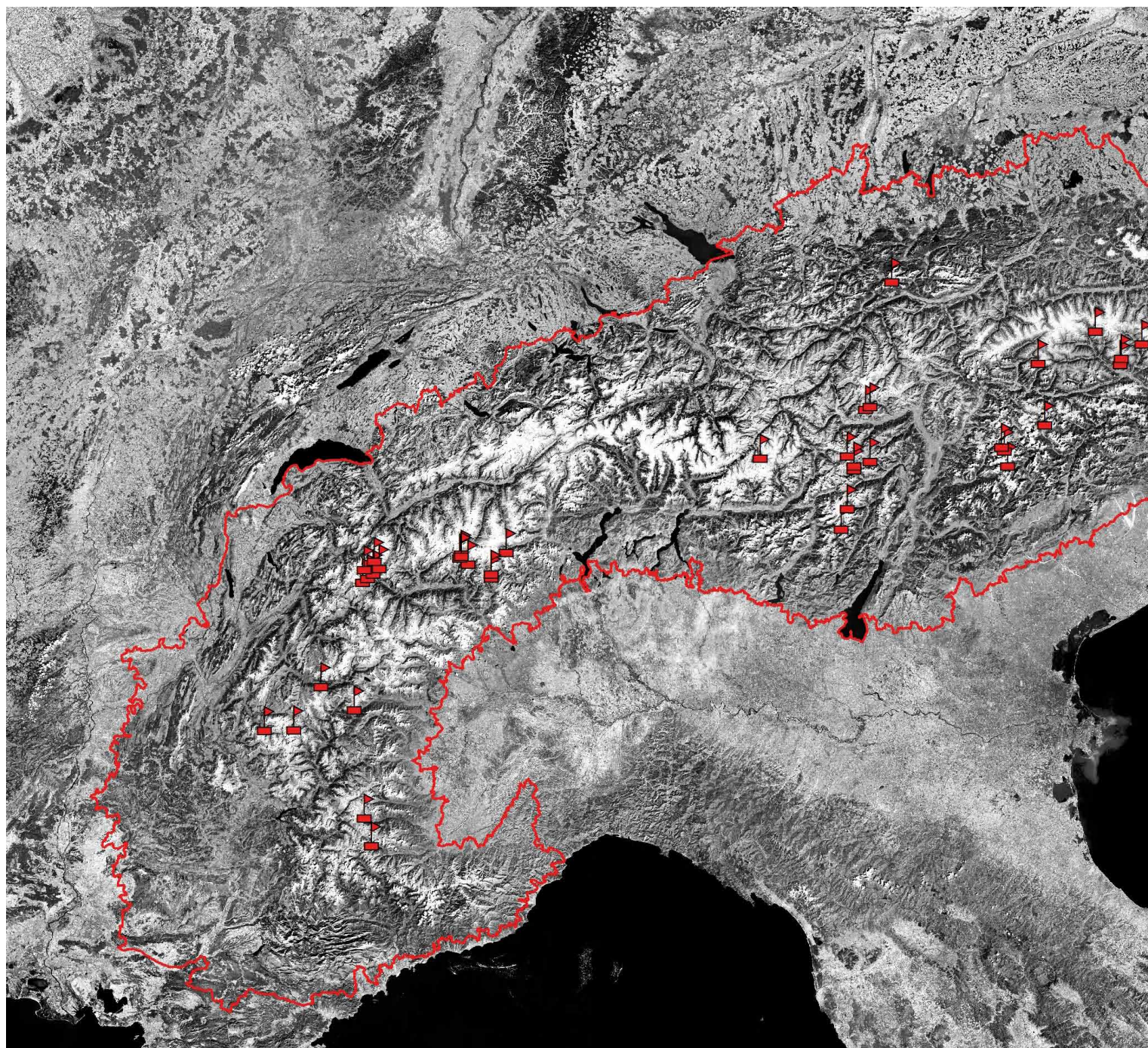
On selected locations, new monitoring stations have been installed and instrumented.

The Alpine-wide monitoring network now was extended by more than 40 monitoring sites that measure various pa-

rameters and characteristics of permafrost in rock and debris-covered soils.

The installation of new monitoring stations was financed in part by the PermaNET project, whereas the long-term maintenance is guaranteed by the institute or authority that installed the instruments.

Following the example of the Swiss permafrost monitoring network PERMOS, national permafrost monitoring networks have been founded. In France, the PermaFRANCE network was established. In Italy and Austria, national monitoring networks are in preparation. The national monitoring networks are coordinating the monitoring activities on



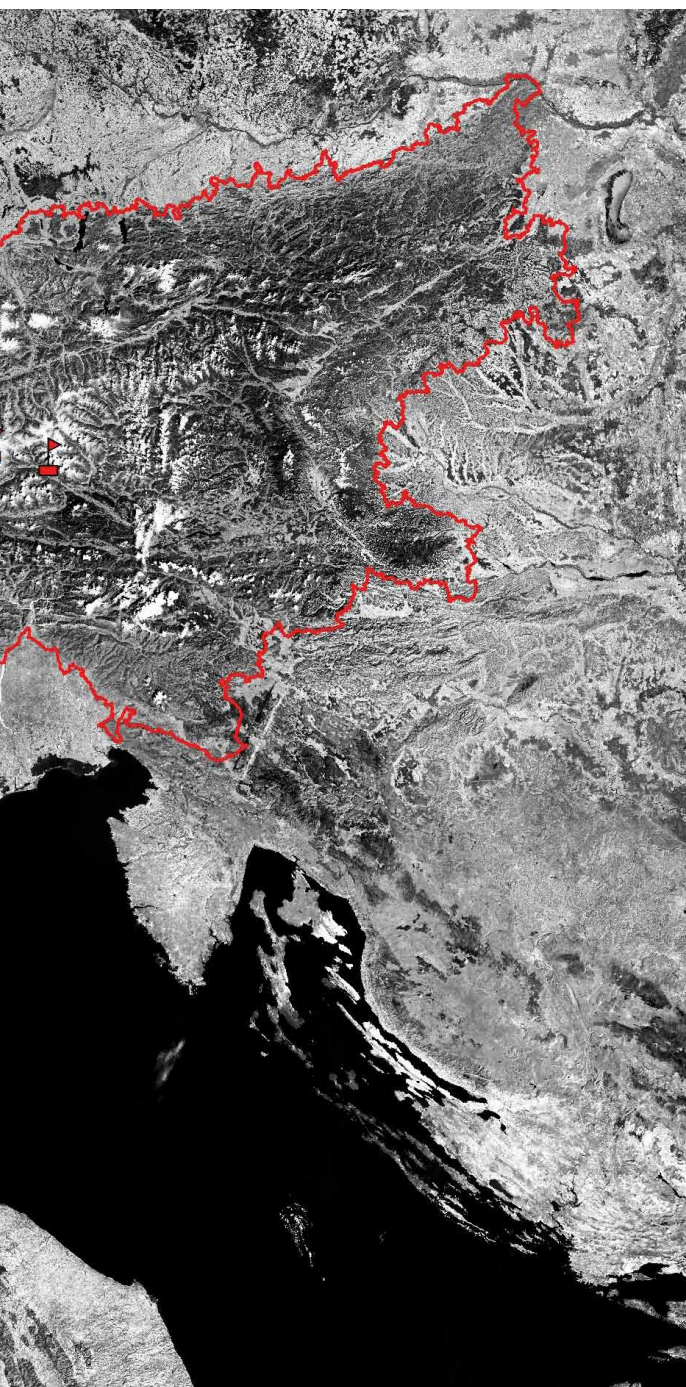
**Fig. 1:** Distribution of permafrost monitoring stations in the Alps that are part of the PermaNET monitoring network. The metadata of permafrost monitoring stations will be continuously updated together with the permafrost evidence inventory.



## Permafrost monitoring network

a national scale. All the monitoring sites that make up the permafrost monitoring network are included in the inventory of permafrost evidence (see following section) which periodically updates the numerical summaries of the collected parameters. The monitoring activities will be financed in the long-term by regional, national or international environmental authorities.

A set of guidelines for the installation and maintenance of the monitoring stations has been developed so that the monitoring network can be extended and guarantee the compatibility of the measured data.



A list of the installed permafrost monitoring stations and guidelines for the installation of permafrost monitoring stations can be viewed and accessed at:

[www.permanet-alpinespace.eu/products/monitoringnetwork](http://www.permanet-alpinespace.eu/products/monitoringnetwork)

Permafrost monitoring stations established or extended within the PermaNET project.

A-1	Hinteres Langtal
A-2	Weissen Cirque
A-3	Dösen Valley
A-4	Hoher Sonnblick
A-5	Goldbergspitze
A-6	Hochreichart
F-1	Orelle
F-2	Laurichard
F-3	Deux Alpes
F-4	Aiguille de Midi
F-5	Les Drus
F-6	Bérard
F-7	Casse des Clausins
F-8	Foréant
F-9	Dérochoir
D-1	Zugspitze
I-1	Senales - Grawand
I-2	Senales - Lazaun
I-3	Ultimo - Rossbänk
I-4	Riva di Tures - Napfen
I-5	Braies - Croda Rossa „Cadin del Ghiacciaio“
I-6	Braies - Croda Rossa „Cadin di Croda Rossa“
I-7	Passo Gardena - Lech del Dragon
I-8	Solda - Madritsch
I-9	Cavaion (GST)
I-10	Cavaion (borehole)
I-11	Lobbie
I-12	Presena
I-13	Cima Uomo
I-14	Matterhorn Carrel South
I-15	Matterhorn Carrel North
I-16	Matterhorn Cheminee new
I-17	Matterhorn Cheminee old
I-18	Matterhorn Oriondè - frac
I-19	Matterhorn Oriondè – not frac
I-20	Col d'Entrevres South
I-21	Col d'Entrevres North
I-22	Grandes Jorasses South-right
I-23	Grandes Jorasses South-left
I-24	Col Peuterey North
I-25	Aiguille Marbree
I-26	Cime Bianche Pass - shallow
I-27	Cime Bianche Pass - deep
I-28	Piz Boè
I-29	Mt. Moro Pass
I-30	Salati Pass Mosso Inst.
I-31	Salati Pass Corno dei Camosci
I-32	Sommeiller Pass
I-33	La Coletta Pass
I-34	Gardetta Pass

Switzerland was the first country in the Alps that coordinated the permafrost monitoring activities on a national scale. All the permafrost monitoring stations in Switzerland are coordinated by PERMOS ([www.permos.ch](http://www.permos.ch))

PERMOS and PermaFRANCE are summarizing periodically the monitoring data.



### Permafrost distribution in the Alps

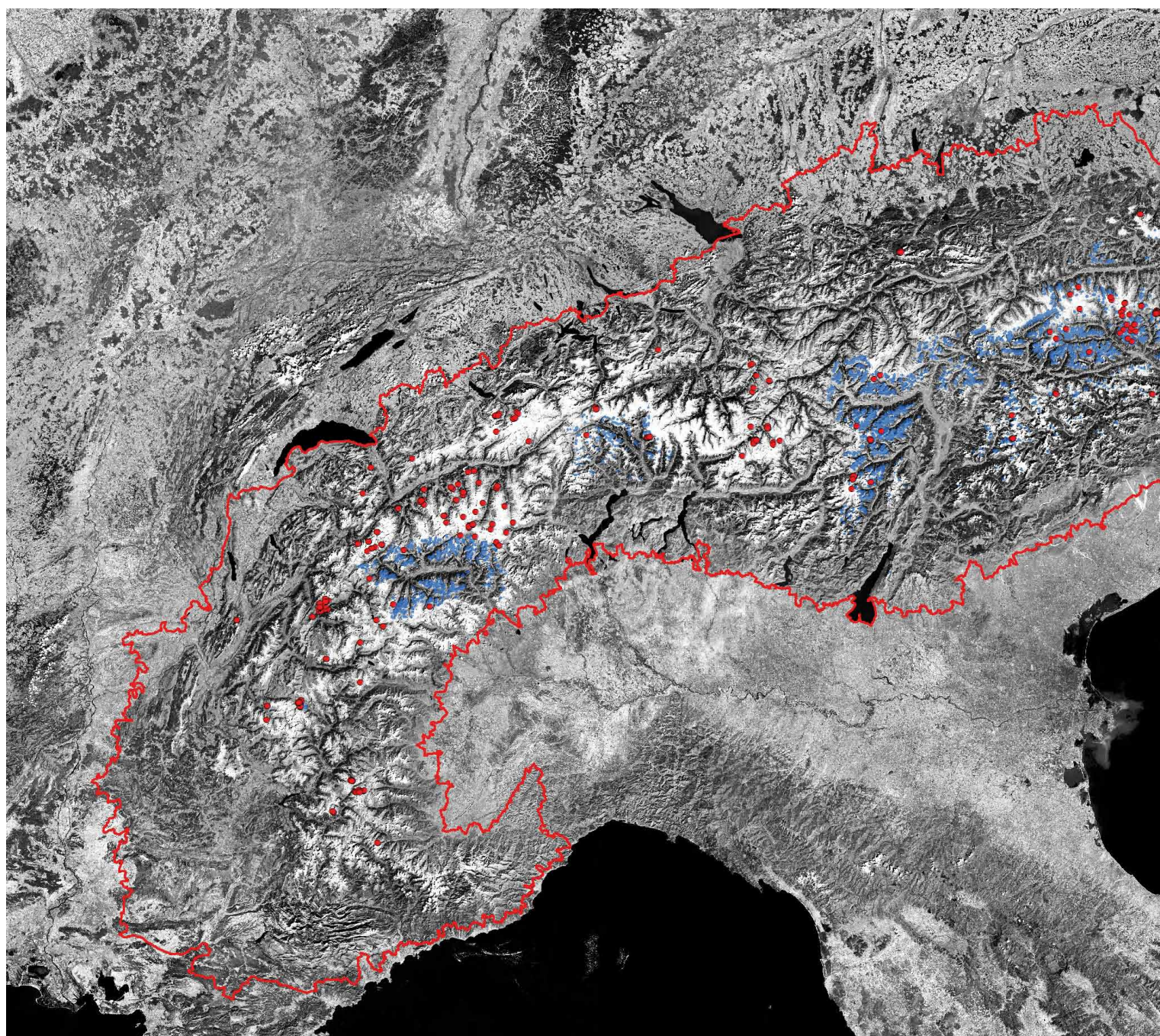
One of the main objectives of PermaNET was to provide a consistent map of permafrost distribution in the Alps. An inventory was developed and compiled that shows the locations where the existence or absence of permafrost was determined. This was the basis for developing the statistical model for the elaboration of the permafrost distribution map.

### Inventory of permafrost evidence

As a basis for the permafrost model covering the entire Alps, evidence of the presence or absence of permafrost from

many countries and institutions has been standardized and inventoried. This inventory only has a few variables to allow researchers to easily insert their data into the database. It contains evidence based on borehole temperature, ground surface temperature, rock-fall scars, trenches or construction sites, surface movement, geophysical prospecting and rock glaciers. The rock glacier inventory is managed separately from the point types of evidence: individual rock glacier inventories are supplied as a collection of polygons that are merged into one rock glacier inventory.

The development of the inventory was supported by the PermaNET observers „University of Zurich“ and „WSL Swiss Federal Institute for Snow and Avalanche Research SLF“.



**Fig. 2:** Map of the permafrost evidence inventory. Presently, more than 400 points of evidence (red dots) and nearly 5000 rock glaciers (blue polygons) are contained in the homogenized inventory.



## Permafrost distribution in the Alps

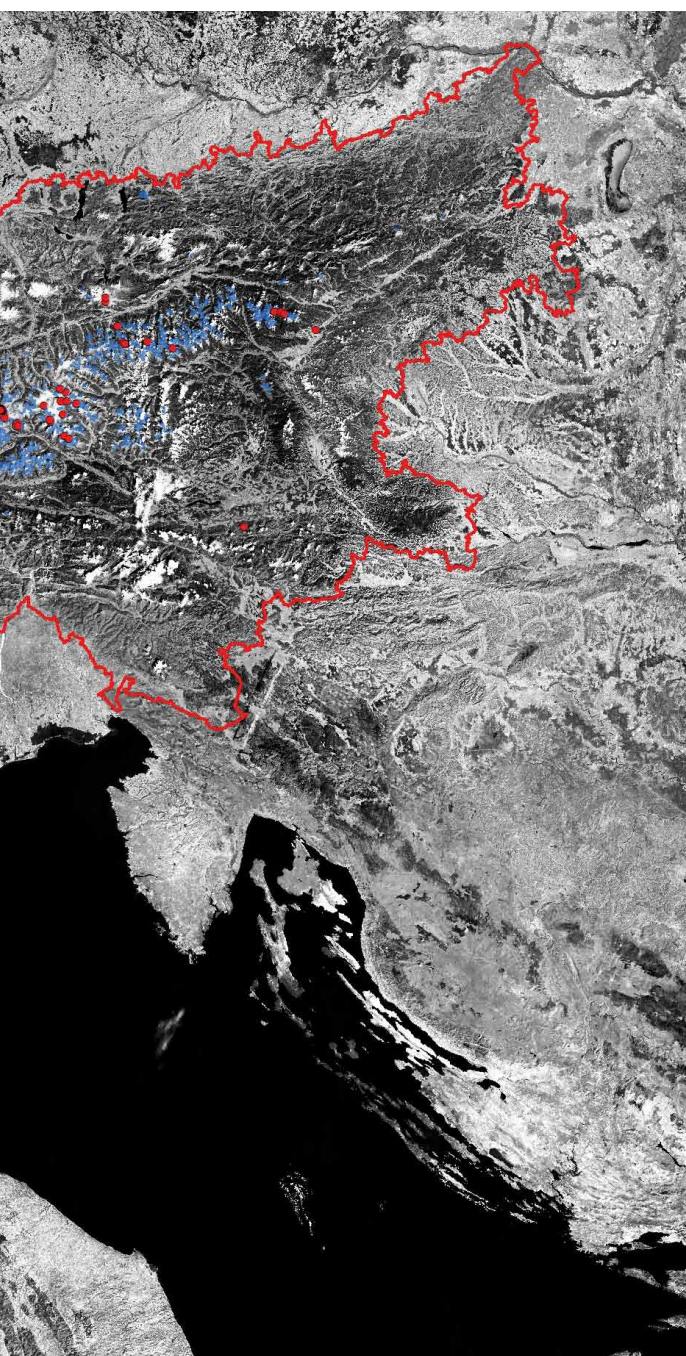
Besides the PermaNET team, thirty-five individuals and institutions provided valuable data. Contributors provided information from their own research areas, consisting of existing data and knowledge adapted to the common data format used in this inventory. This was complemented by specific investigations in collaboration with regional/local geological services, ski resort operators, engineering companies and alpine guide societies.

The total number of point-type permafrost evidence is 408 (April 2010), extending from 44.29 to 47.47° N and from 5.91 to 14.88° E and covering all Alpine countries except Monaco, Liechtenstein and Slovenia. The rock glacier dataset includes seven inventories from Italy, Austria, Switzer-

land and France with a total number of 4795 rock glaciers. The seven inventories are regional (Valle d'Aosta, Piemonte, Veneto, Trentino–Alto Adige in Italy, Massif du Combeynot in France, Ticino in Switzerland and central and eastern Austria) and thus do not cover the entire European Alps. However, the inventory is published as a database on the internet and users can continue to add permafrost observations and evidence data after project closure.

The **permafrost evidence inventory** can be viewed and accessed at:

[www.permanet-alpinespace.eu/products/PED](http://www.permanet-alpinespace.eu/products/PED)



Examples of permafrost evidence:



Trenches with ground ice visible. Photo: X. Bodin



Rock glacier. Photo: X. Bodin





Rockfall scar with exposed ice. Photo: L. Trucco

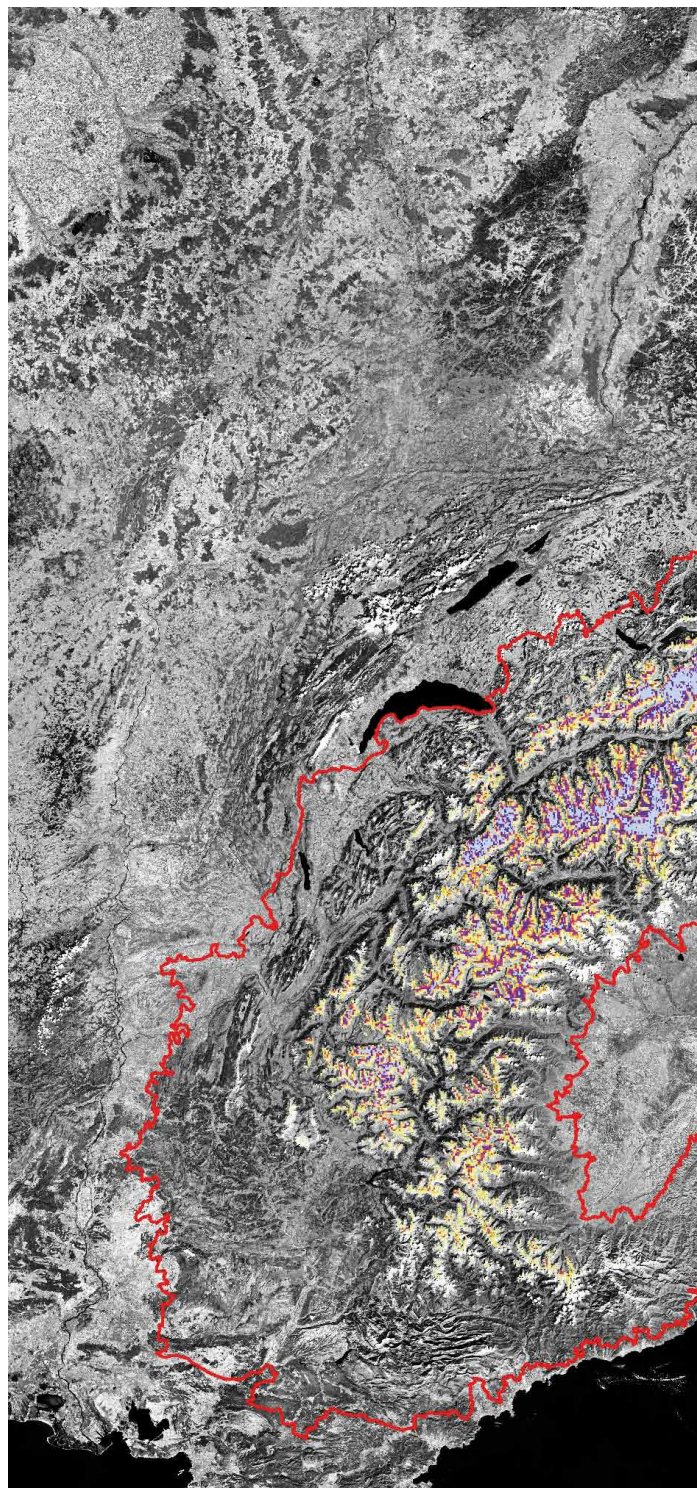


Boreholes. Photo: P. Deline

### Permafrost distribution model

The statistical permafrost distribution model that has been developed has two sub-models, one for debris areas and one for steep bedrock slopes. They are calibrated using the rock glaciers and rock temperature measurements from the evidence inventory. The explanatory variables are mean annual air temperature, potential solar radiation and mean annual precipitation. These can be calculated for the entire Alps and are used to derive estimates of the probability of rock glaciers being intact or of rock face temperature being below 0°C. This quantitative model however needs to be

augmented with additional information because one would also like to know the properties of areas that are not rock glaciers or steep bedrock slopes. This is done by introducing offset terms that are derived from published research and that describe how much warmer or colder certain types of terrain are than what would be expected in the model. Because the definition of these offsets has a degree of subjective choice, the model result is no longer considered to be a probability but referred to as a permafrost index.





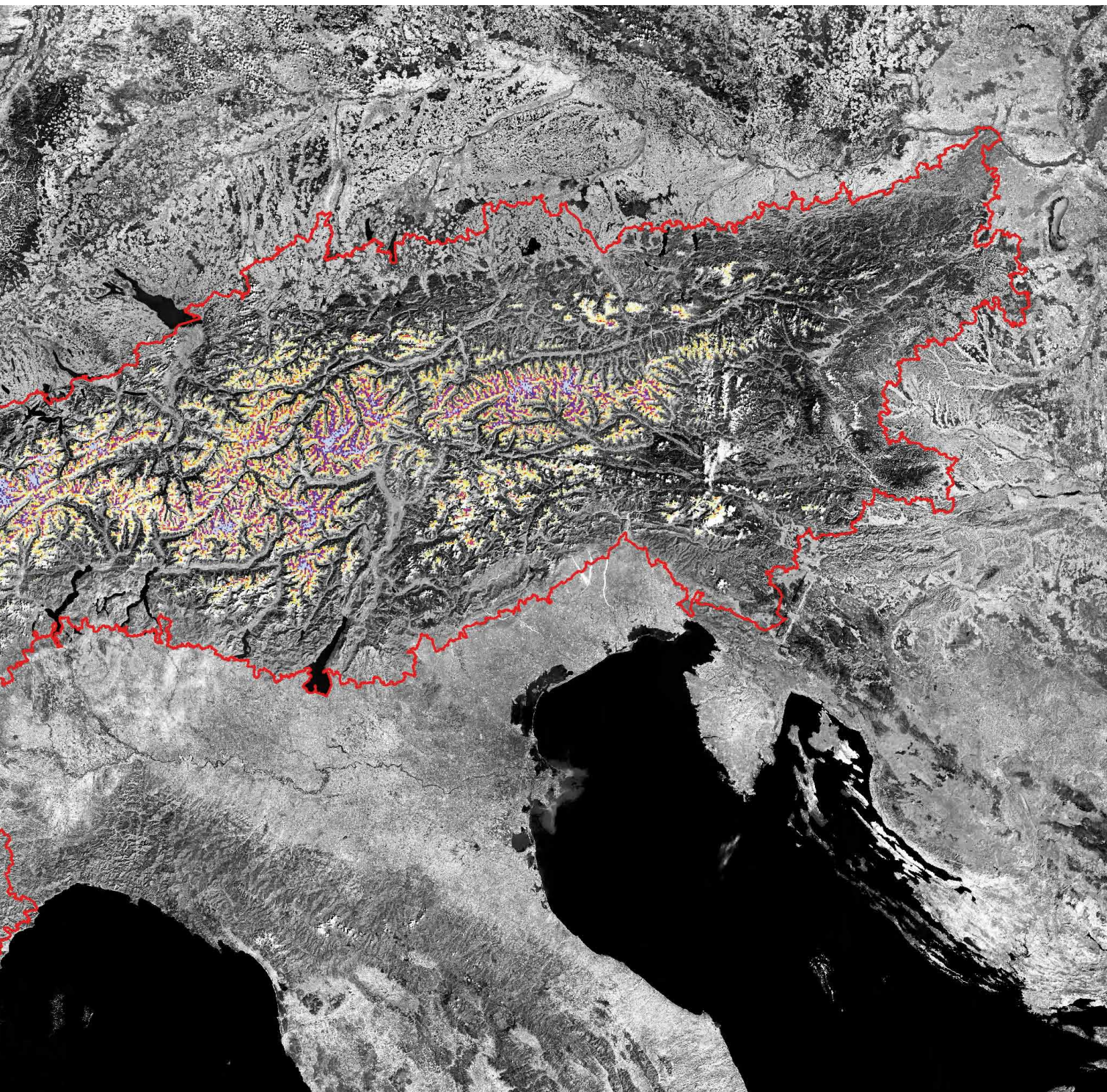
## Permafrost distribution in the Alps

### Permafrost map

The final permafrost map shows the colour-coded permafrost-index that is usually overlaid on a base map for reference. Glaciers, that by definition are not permafrost, are shown with an own signature. The map legend is always accompanied by an interpretation key that allows refining the estimate with local information about ground conditions. The map has been elaborated by the PermaNET observer University of Zurich in collaboration with the Per-

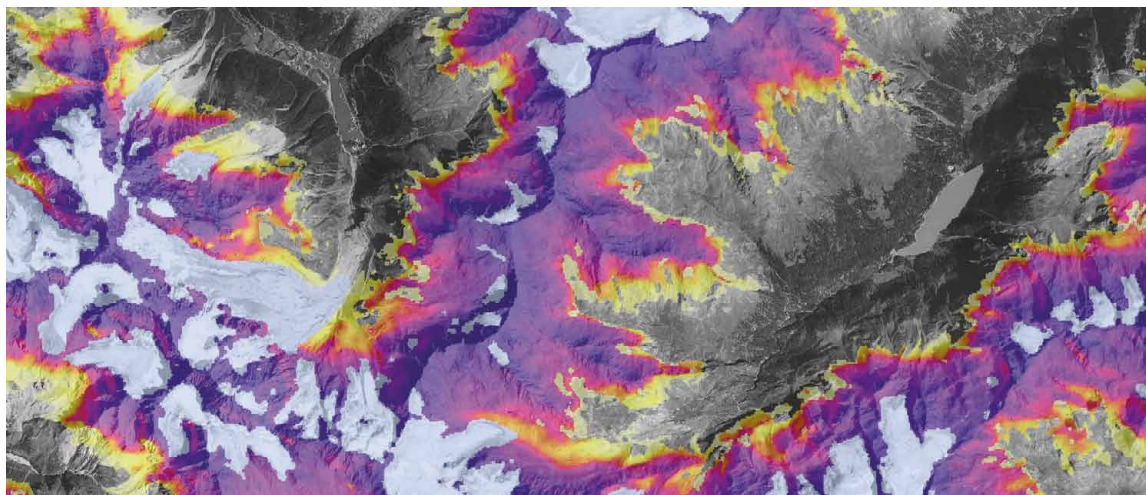
maNET team and is freely available as a GIS layer or online for globes such as Google Earth with a spatial resolution of approximately 30 m.

The **permafrost map** can be viewed and accessed at: [www.permanet-alpinespace.eu/products/pfmap](http://www.permanet-alpinespace.eu/products/pfmap)



**Fig. 3:** Map of the modelled permafrost distribution in the Alps.









**Fig. 4:** Local sample of the final Alpine Permafrost Map. The colour-coded permafrost index is overlaid onto a base map for reference.

### Map Legend

This map shows a qualitative index describing how likely permafrost exists. It is consistent for the entire Alps and intended for practical use by e.g., public authorities or during infrastructure planning and maintenance.

	<b>Blue:</b> Permafrost in nearly all conditions
	<b>Purple:</b> Permafrost mostly in cold conditions
	<b>Yellow:</b> Permafrost only in very cold conditions
	<b>Glacier</b>

Some important local factors such as sub-surface material or snow conditions are not or only approximatively accounted for in the map. However, they can cause strong differences in ground temperature in otherwise equal topographic situations. For this reason, the map legend is accompanied by the **interpretation key**, shown on the right, that can be used to locally further refine the estimate shown on the map. As an example, one would not expect permafrost in fine material (B) or in homogeneous rock (H) where a yellow signature is shown on the map. In special circumstances, permafrost can exist outside the area of the color signature shown. The map shows estimated conditions; more certainty can locally be achieved by e.g., geophysics or boreholes.

This map has been compiled at the University of Zurich, Switzerland within the framework of the Project PermaNET.

Boeckli, L., Brenning, A., Gruber, S. & Noetzli J. 2011: A statistical permafrost distribution model for the European Alps, *The Cryosphere Discussions*, 5, 1419-1459, [www.the-cryosphere-discuss.net/5/1419](http://www.the-cryosphere-discuss.net/5/1419)

Paul, F., Frey, H. and Le Bris, R. (subm.): A new glacier inventory for the European Alps from Landsat TM scenes of 2003: Challenges and results. *Annals of Glaciology*, 52(59).

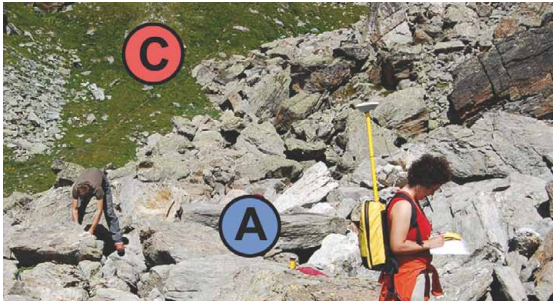


Photo: J. Fiddes



Photo: J. Fiddes

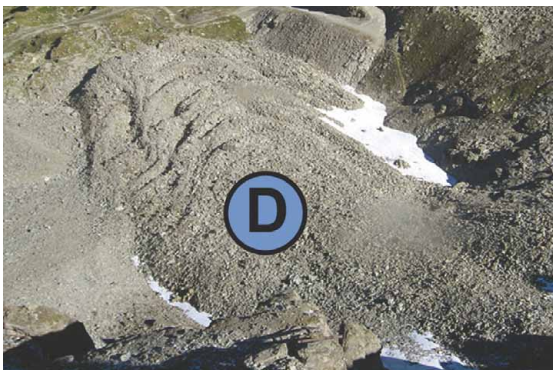


Photo: S. Gruber

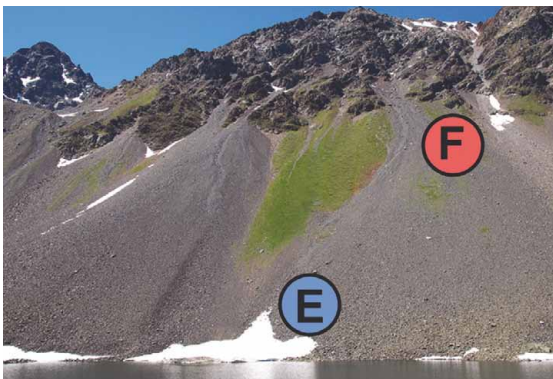


Photo: M. Phillips



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### Interpretation Key

#### Clast size, soil properties and vegetation

A cover of coarse blocks with open voids and no infill of fine material (A) indicates cold conditions. Bedrock, fine-grained soil or soil with coarse blocks but an infill of fines (B) indicate warm conditions. A dense vegetation cover (C) usually indicates the absence of permafrost.

#### Rock glaciers

Active (intact) rock glaciers (D) are identified by signs of movement such as steep fronts. They are reliable visual indicators of permafrost within their creeping mass of debris but do not allow easy conclusions on adjacent areas.

#### Slope position and long-lasting snow-patches

The position along a slope can affect ground temperatures through the sorting of clasts, air circulation within the slope, and snow re-distribution. Often, the foot of slope (E) has colder ground temperatures. It contains more coarse material and is affected by long-lasting avalanche snow. Similarly, other late-lying snow patches indicate locally cold conditions. The top of slope (F) often has locally rather warm conditions. Frequently, it contains smaller clasts as well as an infill of fine material.

#### Steep rock slopes

Steep rock slopes have differing degrees of heterogeneity caused by micro-topography and fracturing. Higher heterogeneity (G) often enables a thin snow cover as well as ventilation and deposition of snow in large fractures, indicating locally cold conditions. Steep, smooth and largely unfractured rock (H) is indicative of warmer conditions. This effect is more pronounced in sun-exposed than in shaded locations.



## Permafrost and related natural hazards

The WP6 dealt with the relationship between permafrost and natural hazards under changing climatic conditions. The working group evaluated several methods for detection and monitoring of permafrost-related slope movements and made recommendations for risk management in areas affected by permafrost degradation.

### Which hazards are related to permafrost?

A state of the art report about permafrost-related hazards and permafrost degradation was elaborated. Its four chapters deal with rock glaciers, debris flows, rockfalls, and local ground movements and their effects on infrastructure. Each chapter summarizes present knowledge about these processes and their relationship to the climate change, and is illustrated by several recent case studies in the Alps. These case studies show the variety of effects on infrastructures in high mountain areas.

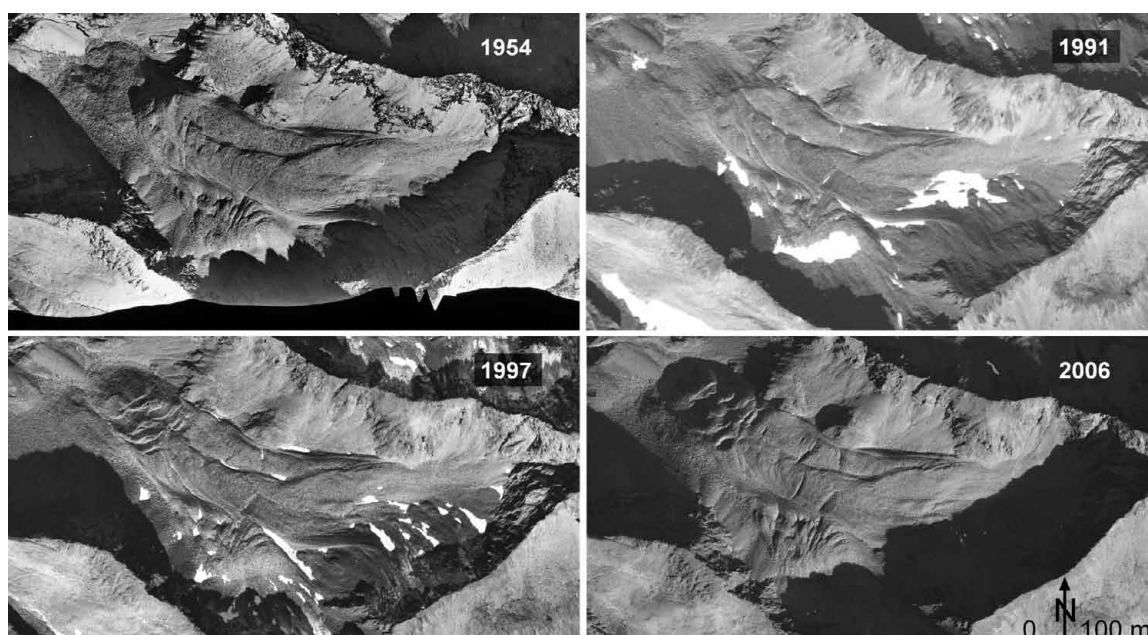
### What can occur if climate changes modify permafrost regimes?

Rock glaciers are creeping accumulations of debris, usually moving at a rate of cm or dm per year. Observed rock glacier dynamics show climatically-induced variations in velocity. In most cases only moderate velocity changes occur, related to annual changes of the mean annual ground surface temperature: an increase in ground temperature induces an acceleration of movements, and inversely. In some cases, a very strong and non-reversible acceleration, up to decameters per year, was observed. This can generate rockfall activity at the rock glacier front, and progression or even rupture and collapse of its front (Fig. 5 and 6).

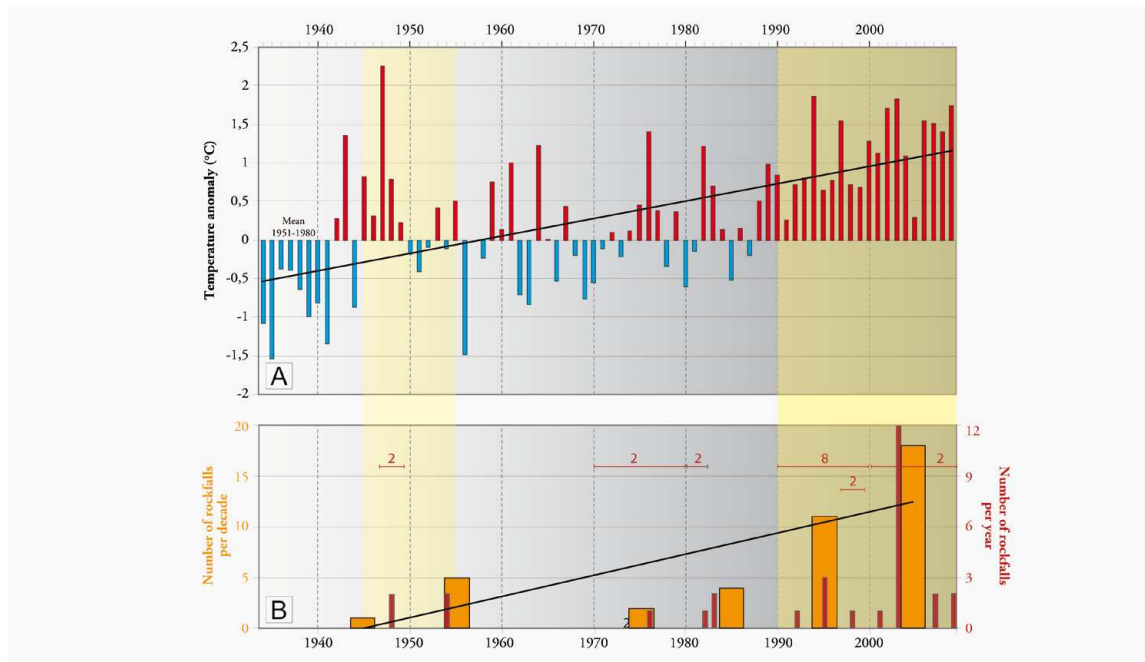
All **surface movements** can cause damage to infrastructures built on the moving terrain. Small movements can be accommodated by adapted design, but the potential accelerations induced by climate warming could challenge even these. In any case, building on permafrost induces additional construction and maintenance costs, and reduces the lifetime of infrastructures.

**Rockfalls** generate risks for mountaineering activities in the Alps and infrastructure like cable cars, mountain railways and roads, or ski resorts. Rock avalanches can threaten valley inhabitants at long distance from the source area. Climatically-driven degradation of rockwall permafrost is probably one of the main triggers of recent, present and future rockfalls (Fig. 6), as suggested by the massive ice that was observed in several starting zones, and the increase  $> 1^{\circ}\text{C}$  of the mean annual air temperature in the Alps during the 20th Century, accelerated since the 1980s.

Where rock glacier fronts overhang steep slopes, secondary processes can mobilize the released debris downslope. This and rockfall activity in permafrost areas can increase, for instance, the debris supply and thus the volume of debris flows. Permafrost can influence **debris flow** activity in different ways, mainly by increasing the debris supply to the torrential system, but also by influencing the water runoff characteristics. But, the influence of permafrost on debris flow activity depends mostly on the specific characteristics of the torrent catchment. The melting of ice in permafrost soils or scree slopes in the course of active layer thickening can lead to the loss of internal ice as stabilising binding material. This can lead to the increased availability of erodible material, to the subsidence of soils in flat



**Fig. 5:** Aerial photographs of the Hinteres Langtalkar rock glacier (Austria) between 1954 and 2006. Formation of crevasses and disintegration through active sliding processes since 1994 at its frontal part. Aerial photographs by Austrian Federal Office of Metrology and Surveying (BEV), courtesy of V. Kaufmann and R. Ladstädter.



**Fig. 6:** Comparative evolution of climate in Chamonix (1040 m a.s.l.) and rockfalls in the North side of the Aiguilles de Chamonix (Mont Blanc massif, France). A: mean annual air temperature anomaly in relation to the 1951 – 1980 mean; B: rockfalls number per decade and per year. Black line: trend (linear regression, decadal for B); wide bars in B: rockfalls not precisely dated. (Meteorological dataset: Météo-France).

areas and to slope movements in inclined slopes. In steep slopes, permafrost influences hydraulic conductivity and overall slope stability. In summertime, the active layer is often saturated because of the characteristics of the permafrost table as aquiclude. Thus, infiltration capacity is low and superficial runoff is high. The permafrost table can act as a slide horizon for landslides in the active layer. Consequences of this can be the sliding of debris cover, the settling of debris and related slope movements or landslides. The melting of ground ice contributes to the formation of thermokarst phenomena and thermokarst lakes with subsequent lake outburst floods.

#### Which actions are needed to face increasing risks in affected locations?

The described processes related to permafrost and permafrost degradation do not influence hazard situations over wide areas. However, in single cases they could have a remarkable influence on hazard and risk situations. The first step in each planning activity is to refer to the permafrost distribution map. If the map shows a possible presence of permafrost at the study site, the use of permafrost detection methods as described in the PermaNET handbook is recommended. If permafrost is to be considered, special monitoring methods support the analysis of the processes. In order to evaluate operational approaches for detection and monitoring of slope movements and ground temperature in permafrost areas, six method sheets were established about dGPS, GPR, DInSAR, ERT, TLS, and terrestrial photogrammetry. Basic principles of each method are summarized, before listing their possible applications, and the main results, opportunities and limitations; each sheet is completed with

references and illustrated with some figures. Comparisons between some pairs of these methods were realized, and a SWOT analysis completed this assessment.

Recommendations were made to reduce hazards in a permafrost environment. For example: (i) infrastructures on an active rock glacier and its front zone should be avoided; (ii) a security zone should be observed below an overhanging rock glacier; (iii) trails crossing rock glaciers or passing down below its front should be regularly checked.

The **state of the art report of natural hazards in permafrost areas** and the **handbook for mountain permafrost detection and mapping** can be viewed and accessed at:

[www.permanet-alpinespace.eu/products/permafrost hazards](http://www.permanet-alpinespace.eu/products/permafrost hazards)



**Fig. 7:** DGPS reference station on a fixed survey point in front of the Reichenkar rock glacier (Austria). Photo: K. Krainer

## Permafrost and climate change

High altitude and high-latitude regions are generally recognized as being particularly sensitive to the effects of climate change. A large proportion of permafrost in the European Alps, for instance, is at or close to melting point and is therefore very sensitive to atmospheric warming.

### Thermal and geomorphic permafrost response to present and future climate change

Possible thermal and geomorphic effects are manifold and the possible thermal reactions of permafrost include:

- (a) Increasing ground temperature and therefore permafrost warming;
- (b) Thawing of permafrost with three effects: reduction in the spatial extent of permafrost areas, thickening of the seasonally unfrozen layer, and increasing ground-water circulation and pressure;

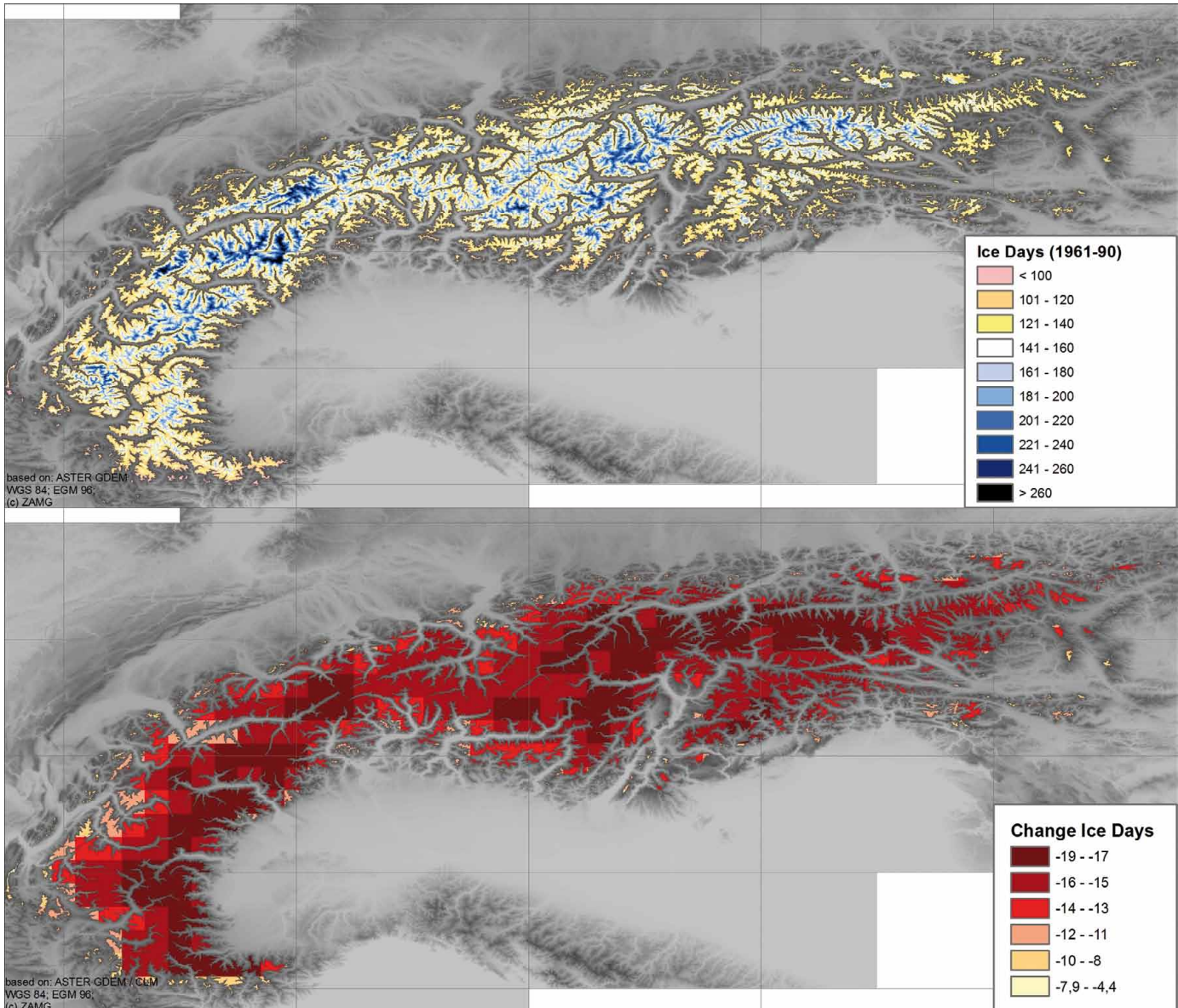
(c) Changes in the number and characteristics of freeze-thaw cycles.

Possible geomorphic permafrost reactions include:

- (a) Changes in the rate of rock glacier displacement (vertically and horizontally);
- (b) Changes in displacement mode of rock glaciers (from creep to initiation of basal sliding or even collapse);
- (c) Changes in cryogenic weathering;
- (d) Changes in the volume and extent of unstable slopes;
- (e) Changes in frequency and magnitude of mass movement events such as rockfalls, rock slides or debris flows.

### Case studies in the European Alps

PermaNET was concerned with the understanding of thermal and geomorphic permafrost response to present and future climate change. To achieve this aim, research was carried out in more than 10 different study sites distribut-



**Fig. 8:** Ice days (1961–90) and estimated difference in Ice days between 1961–90 and 2021–2050 above 1800 m a.s.l. Source: ZAMG.



ed over the entire European Alps in Austria, Switzerland, France and Italy. In a first step, present and future climate change was analysed and modelled focusing on frost-, ice-, and freeze-thaw days between the two climate periods 1961–90 and 2021–2050 in the Greater Alpine Region/GAR (Fig. 8). Second, the results of the climate change analysis were combined with the data from the study sites by analysing the recent thermal and/or geomorphic evolution of a relevant landform and its possible future response to predicted climate change. The study reveals the range of possibilities how permafrost is reacting in a warming climate, two examples are briefly presented here.

### Example 1: Rockfalls in the Mont Blanc Massif

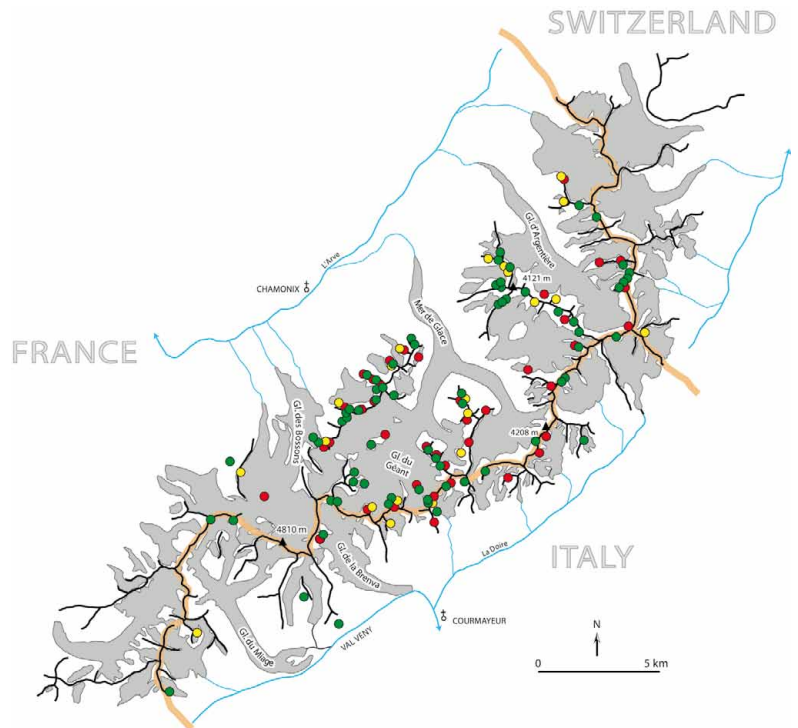
A total of 139 rockfalls have been documented between 2007 and 2009 in the central area of the Mont Blanc massif, 53 of them were precisely dated. Among them, 51 rockfalls occurred during the hottest months of the year and 38 occurred after a period of increasing mean daily air temperatures of at least two days (Fig. 9). Important is the observation that the hotter the summer, the higher the elevation of the rockfall scar. This indicates for the future that rockfalls will occur at higher elevations not affected earlier with implication to people and infrastructure at the new areas of rockfall release, transport and deposition.

### Example 2: Rock glacier velocities in Central Austria

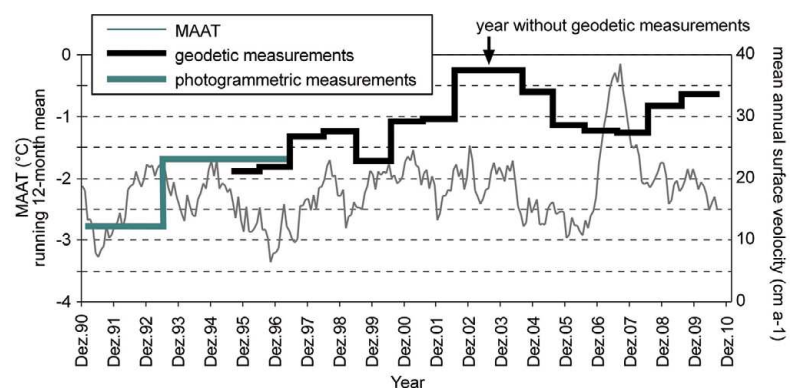
Active rock glaciers are creeping phenomena of permafrost. Their movement is strongly related to climatic conditions and consequently to ground temperatures. As shown by different studies, the movement pattern of the monitored rock glaciers in the European Alps correlated with each other during the last years to decades. At the Dösen Rock glacier in Central Austria for instance, two peaks of high surface creep were detected in 2003–2004 and 2008–2010 (Fig. 10). The velocity pattern indicates that this rock glacier reacts more quickly after a cool period with deceleration. In contrast, the rock glacier needs more time to react to warmer periods with acceleration of the movement related to the inertia of the rock glacier system towards ground warming and velocity changes. This indicates for the future that predicted climate warming will first cause an increase of the creep velocities of rock glaciers. However, in a later stage this will lead to inactivation of many presently active rock glaciers. Some degrading rock glaciers may even entirely collapse and are consequently sources for natural hazards.

The report about the thermal and geomorphic permafrost response of permafrost to present and future climate change in the European Alps can be viewed and accessed at:

[www.permanet-alpinespace.eu/products/permafrostresponse](http://www.permanet-alpinespace.eu/products/permafrostresponse)



**Fig. 9:** Documented rockfalls in the Mont Blanc massif in 2007 (red dots), 2008 (yellow dots) and 2009 (green dots).



**Fig. 10:** Mean annual air temperature/MAAT (running 12-month mean) and horizontal surface creep at the Dösen Rock Glacier between 1990 to 2010.

### Permafrost and water resources management

There is still little knowledge on the impact of climate change on alpine permafrost and how the enhanced melting of permafrost ice alters discharge patterns and water quality of alpine headwaters. Rising air temperature has caused the release of highly concentrated meltwater from active rock glaciers. In response to the enhanced release of ions and heavy metals high altitude lakes, which are drained by meltwater from rock glaciers, can experience a substantial change in water chemistry. In particular, the high concentrations of Ni may strongly exceed the limit of drinking water as has been found in meltwater draining from active rock glaciers and glaciers at Schnalstal (Ötztal Alps). The ice content of alpine permafrost like rock glaciers is still unknown. However, the hydrological regime of active rock glaciers is strongly driven by the amount of water stored as ice in permafrost ground. To study the hydrological regime of active rock glaciers and their response to climate change discharge, water temperature, electrical conductivity and water chemistry (anions, cations, heavy metals) of rock glacier springs were determined at Lazaun (Schnalstal) and compared to glacial meltwater streams and springs not impacted by permafrost. Core drillings were performed at two active rock glaciers (Lazaun – Schnalstal and Rossbänk – Ultental). The cores were documented in detail and are currently being analyzed for ice-content, ice-chemistry, stable isotopes and palynology. The drill holes were instrumented with temperature loggers and inclinometers to obtain information on the thermal characteristics and dynamics of the rock glaciers. Core drilling and the hydrological and chemical measurements are supported by sedimentological analysis of the debris mantle of the rock glaciers including clast rock types, grain size, grain size distribution (sorting), rounding and orientation of the clasts on the surface, content of fine-grained matrix, thickness and structure of the debris mantle, mineralogical and geochemical composition and the ice content of the uppermost frozen layer. Additional information on the thickness, internal structure and ice content of active rock glaciers and per-

mafrost ground is achieved by geophysical methods such as ground penetrating radar.

Climate change induced permafrost degradation may have major impacts on ecosystems, landscape stability and on people and their livelihoods.

We recommend that springs derived from glaciers or alpine permafrost should be studied carefully at least for one hydrological year concerning water quality (anions, cations, heavy metals, bacteria), suspension load, temperature and discharge before such springs are used for drinking water supply.

The **report of „Permafrost and water resources management“** can be viewed and accessed at: <http://www.permanet-alpinespace.eu/products/pfwaterresources>



Discharge measurements. Photo: K. Krainer



Ice sample from rock glacier. Photo: D. Tonidandel





Drillings on rock glacier. Photo: D. Tonidandel



### Recommendations for decision-makers

The interdisciplinary and integrated approach of compiling the existing knowledge about permafrost in the European Alps resulted in many valuable products that can be used in natural hazard management practice and in territorial planning.

The main outputs of the PermaNET project were

- the Alpine Space permafrost monitoring network and related handbooks,
- the inventory of permafrost evidence,
- the map of permafrost distribution in the Alps,
- guidelines for the consideration of permafrost in risk management.

The permafrost monitoring network extends the knowledge databases of the thermal state of permafrost in the Alps and allows the monitoring of the future thermal response of permafrost to climate change. On one hand, this long-term monitoring network allows the ongoing signal of global warming to be recorded and on the other hand it provides fundamental data for assessing the consequences of climate changes to permafrost and related natural hazards.

The elaborated permafrost distribution datasets provide a decision base for interpreting observed changes in the landscape. For the planning sector, the permafrost inventory and the map provide a decision base for choosing adequate methods for detailed field investigations.

If the map indicates the possible presence of permafrost at a specific location where problems with ground movements exist or where infrastructure is planned, the elaborated handbooks for permafrost detection and monitoring could provide the basis for deciding what techniques should be used.

With these products, PermaNET contributed to optimizing the decision bases in territorial planning, natural hazard management and water resources management.

Summarizing the main findings of PermaNET, the following recommendations could be formulated:

1. The knowledge about permafrost and the effects of climate change on permafrost phenomena and related hazards is fragmented and on different levels of development within the Alps. The assemblage of all experience and measurements into one knowledge base provides a sophisticated decision base and led to the development of a consistent map of permafrost distribution in the Alps. To further extend the knowledge base it is essential to continue the interdisciplinary and transnational collaboration.

2. Permafrost phenomena and permafrost degradation show a high spatial variability of occurrence through the

Alps. The state of the art reports of PermaNET provide a collection of different aspects of the topic. Permafrost phenomena and related natural hazards (including the effects of climate change) should be considered in natural hazard and risk management in a common way throughout the Alps. Natural hazards related to permafrost and permafrost degradation are locally restricted to specific cases and should neither be overestimated nor neglected. The phenomenon has to be studied on the site and in detail before making conclusions or decisions in risk management. Some conclusions are valid for many locations: (i) infrastructure upon an active rock glacier and its front zone should be avoided; (ii) a security zone should be observed below a rock glacier; (iii) trails crossing rock glaciers or passing down below its front should be regularly checked.

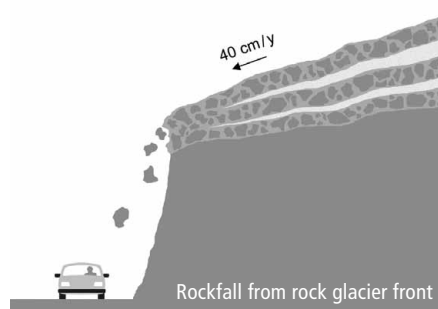
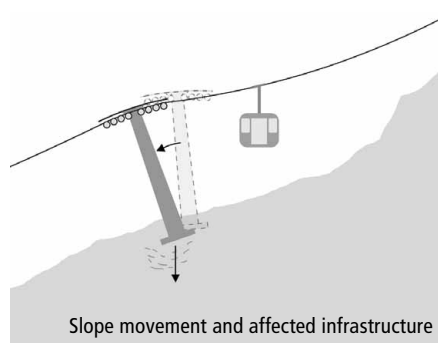
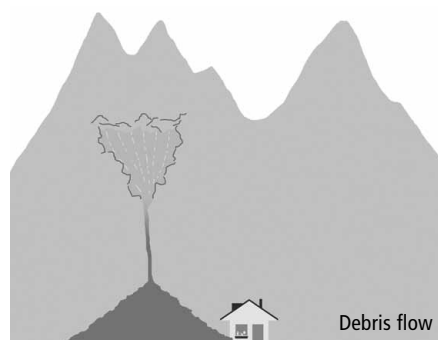
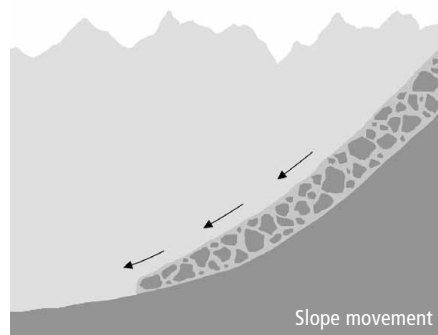
3. For all planning tasks in the high mountain environment it is important to know if permafrost occurrence is possible, and if so, what the possible effects on the planned activity are. A raised awareness of the existence of mountain permafrost and its possible adverse effects on economic activities is helpful for improving the efficiency and sustainability of investments. All stakeholders are invited to make use of the elaborated permafrost map, and to add their own observations to the permafrost evidence inventory. With this support, the databases will be extended and the knowledge of permafrost distribution will grow.

4. In case of slope deformations in permafrost areas, slope monitoring techniques are crucial tools for risk assessment and risk prevention. Their use must be encouraged. Adequate time is required for analysing the problem in detail. Monitoring of slope movements in permafrost areas require specific methods and must meet specific needs. All stakeholders are invited to make use of the elaborated handbook for permafrost detection and permafrost monitoring. It provides hints for choosing the appropriate monitoring technique.

5. In order to exchange experiences, to expand the data series and to foster harmonization, it is necessary to continue the transnational permafrost monitoring network of researchers and practitioners. National environmental authorities are recommended to support the further development of this network of persons and institutions and to financially support the maintenance of the monitoring stations. The effects of climate change to permafrost can only be quantified through long-term monitoring of the evolution of permafrost over a wide area.

### Outlook

The PermaNET project provided the bases for the establishment of a transnational permafrost monitoring network in the Alps. Now, it is up to the stakeholders together with the decision makers to build on these bases and to guarantee the continuity of permafrost monitoring. The PermaNET project partners and partner institutions will continue to maintain and improve the monitoring network. The next step is to define a way to coordinate the transnational permafrost monitoring network, to compile and analyse permafrost monitoring data to a periodic report of the thermal state of permafrost in the European Alps.



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**Further information:**

The website of the PermaNET project provides detailed reports of the topics described in this brochure. Furthermore, the detailed reports, handbooks and guidelines available at the website provide bibliographies for further information. The PermaNET website offers of web services for viewing and analysing the compiled permafrost evidence inventory and the permafrost distribution map. For further information please have a look to:

[www.permanet-alpinespace.eu](http://www.permanet-alpinespace.eu)





